

Article

Smart Sensing in Italian Historic City Centers: The Liminal Environmental Monitoring System (LEMS)

Valentina Diolaiti ¹, Leonardo Sollazzo ^{1,*}, Giulio Mangherini ^{1*}, Nazim Aslam ¹, Diego Bernardoni ²,
Marta Calzolari ³, Pietromaria Davoli ³, Valentina Modugno ³ and Donato Vincenzi ^{1,2}

¹ Department of Physics and Earth Science, University of Ferrara, Via Saragat 1, 44122 Ferrara, Italy; valentina.diolaiti@unife.it (V.D.); nazim.aslam@unife.it (N.A.); donato.vincenzi@unife.it (D.V.)

² Consorzio Futuro in Ricerca, Via Saragat 1, 44122 Ferrara, Italy; diego.bernardoni@edu.unife.it

³ Department of Architecture, University of Ferrara, Via della Ghiara 36, 44121 Ferrara, Italy; marta.calzolari@unife.it (M.C.); pietromaria.davoli@unife.it (P.D.); valentina.modugno@unife.it (V.M.)

* Correspondence: leonardo.sollazzo@unife.it (L.S.); giulio.mangherini@unife.it (G.M.)

Highlights

What are the main findings?

- A flexible, low-cost Liminal Environmental Monitoring System (LEMS) was designed and calibrated to reliably measure temperature, humidity and solar irradiance in heritage-compatible, liminal spaces.
- Combining LEMS data with a 3D-ray tracing based shading indicator enables a clear separation between geometric shading and meteorological effects in the analysis of microclimate conditions.

What are the implications of the main findings?

- LEMSs provide a practical, heritage-compatible tool to build a dense microclimate monitoring network, supporting conservation and comfort assessment in smart heritage districts.
- The proposed measurement-simulation workflow can be replicated and scaled as a building block for urban digital twins and a smart-city platform.

Abstract

Historic city centers host dense ensembles of heritage buildings where conservation goals must coexist with sustainable and smart urban development, yet the semi-outdoor “liminal” spaces of these complexes, such as cloisters, loggias and courtyards, are rarely included in microclimate monitoring networks. This study develops and tests the Liminal Environmental Monitoring System (LEMS), a flexible environmental data acquisition architecture designed for long-term monitoring in such spaces. The LEMS is based on a custom, low-cost data acquisition board able to handle multiple analogue and digital sensors, combined with a daisy-chain communication layout using the MODBUS RS485 protocol and a commercial datalogger as master, in order to meet the technical and visual constraints of historic buildings. Board calibration and sensor characterisation are reported, and the system is deployed in the cloister of Palazzo Costabili, a renaissance complex in the historic city center of Ferrara (Italy). This case study illustrates how the LEMS captures spatial and temporal variation in air temperature, relative humidity and solar irradiance and how an annual solar-shading indicator derived from 3D ray-tracing simulations supports the interpretation of irradiance measurements. The results indicate that the LEMS is a viable tool for heritage-compatible microclimate monitoring and can be adapted to other historic courtyards and loggias.



Academic Editors: Giancarlo Nota,
Giancarlo Fortino and Pierluigi Siano

Received: 1 December 2025

Revised: 10 January 2026

Accepted: 14 January 2026

Published: 20 January 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: smart cities; environmental monitoring; IoT; data acquisition; smart heritage

1. Introduction

Having been the stage for relevant social and political changes throughout history, Central Europe has conspicuous cultural heritage significance featuring a large stock of monuments and historic districts [1]. This heritage represents a non-renewable resource both in terms of socio-cultural and economic uniqueness [2] and must be protected, while cities transition toward more sustainable and smart urban development. Approximately 35% of the European buildings are more than 50 years old, and, considering the low rate of new building construction in Europe (3%) [3], improving the energy and environmental performance of this existing stock is one of the most important steps towards a sustainable and climate-resilient urban future. However, the necessity to preserve their architectural, social, and historical values [4] may limit the adoption of retrofit solutions based on renewable energy technologies even if they are architecturally integrated [5]. Indeed, the buildings and the broader urban environment are the layered result of a constant dialogue between culture and territory. The willingness to preserve this dialogue, in the context of smart heritage [6], implies paying attention not only to the building envelope and its integrated technologies [7,8] but also to the outdoor and semi-outdoor space that mediates between buildings and the city. The historical texture of European cities is characterized by a rich series of outdoor spaces (such as gardens and parks) and of the so-called transitional or liminal spaces (such as porches, loggias, cloisters and courtyards). Transitional spaces are highly building-integrated and diffuse environmental spaces, straddling the outside and the inside [9–11]. In the traditional architecture, these spaces have been built as environmental control systems, but often their original climatic role has been lost to time and is often overlooked in contemporary management and retrofit strategies. Reactivating and reusing these liminal spaces can contribute significantly to the environmentally sustainable development of cities and to their better preservation. Their improvement directly affects the urban microclimate, contrasting climate change and urban heat island effects [12], thus increasing outdoor thermal comfort of residents and tourists. This would in turn increase the quality of life of citizens and enhance urban tourism routes, boosting economic activities. A comprehensive understanding of buildings' outdoor microclimate, as well as their interaction with the indoor environment [13], is essential to ensure both their correct preservation and to define the appropriate refurbishment procedure [14,15]. In recent years, the field of climate monitoring has seen extensive research with a variety of purposes and research strategies. On the one hand, simulation models have been developed to assess environmental performance of the building before and after implementing rehabilitation measures [16,17]. On the other hand, many monitoring campaigns have been carried out to evaluate how the different building components, namely, the building envelope [18–20] or the climate control system [21–23], affect the visitors' thermal comfort or the indoor climate [24–26]. In contrast, in situ monitoring campaigns of historic outdoor environments are still lacking [26,27], even though field data are essential to characterize the real microclimate of the buildings' surroundings. This lack of systematic outdoor monitoring in historic districts represents a gap for smart-city and digital twin initiatives, which increasingly require high-resolution environmental data to support effective planning and management. Advanced building management systems designed for microclimate monitoring can collect large amounts of data [28], often within broader IoT and smart-sensing frameworks [29]. Nonetheless accurate characterizations of many environmental parameters (air temperature, humidity, sun radiation, wind speed and direction) are often limited to the use of

proprietary hardware and software, which inevitably impacts the cost or flexibility of the data acquisition system [30]. Therefore, there is a significant potential to develop low-cost, modular and flexible IoT devices that make long-term microclimate monitoring in heritage contexts more accessible. In this direction, Silva et al. [31] performed a data acquisition campaign by using prototype breadboards based on the Arduino technology and measuring temperature, relative humidity, ventilation rate and building occupancy. Similarly Karami et al. [32] and Ali et al. [33] developed a wireless data acquisition system based on Arduino Uno boards and an indoor environmental quality sensing system composed by a series of low-cost sensors, monitoring temperature, relative humidity, occupancy, lighting intensity and CO₂ concentration. These contributions demonstrated the feasibility of a low-cost IoT framework for environmental monitoring but are mostly oriented to indoor spaces and may be difficult to integrate in sensitive historic buildings. The aim of this work is to develop and test a Liminal Environmental Monitoring System (LEMS), i.e., a network of smart sensors specifically designed to monitor environmental conditions in liminal spaces of historic buildings and to demonstrate its application to a cloister and a loggia in a dense historic center. In comparison with the toolkits reported in [31–33], the devices presented here are considered as a flexible, modular smart-sensing platform that facilitates the integration of multiple environmental sensors within a single data acquisition board. Given that the aim of this paper was the realization and calibration of a low-cost data acquisition system for the monitoring of environmental conditions in liminal spaces, the used sensors are assumed to be factory-calibrated. The easily adoptable methodology and experimental setup for the monitoring of outdoor spaces in historical buildings could be beneficial for the proliferation of similar monitoring campaigns in heritage buildings across different locations, historical and cultural contexts. This would be crucial narrowing the existing research gap on the topic and understanding the interaction between indoor and outdoor spaces in buildings and the broader cityscape. The birth of a network of smart cities and/or smart heritage buildings would also benefit from a standardized method of selecting the parameters of interest to be monitored [34,35].

The quantitative nature of the data that can be collected with the setup and methodology illustrated in this paper could synergize extremely well with pre-existing frameworks and approaches of historic buildings conservation that are more oriented towards policy-making/government-led interventions [36] or place making [37]. This synergy would prove crucial in the physical preservation of cultural heritage without losing sight of its relationship with the territory and the population living in its vicinity.

2. Materials and Methods

The data acquisition board was developed in-house within the Photovoltaic Laboratory of the University of Ferrara, and it was designed in order to be extremely flexible both from hardware and software perspective. It handles digital and analogue inputs and its configuration and microcontroller firmware can be adapted to different sensor specifications, ensuring a high degree of flexibility with minimal use of external electronic components. The communication architecture and the data transmission protocol were conceived to be IoT-ready but also chosen in response to the specific requirements of the scientific study, the characteristics of the building environment and the historical constraints of the installation context. Although previous studies [31,32] have shown that replacing commercial data loggers with Arduino-based devices coupled with wireless communication can reduce the complexity of wired systems, such solutions may be incompatible with heritage-protection constraints—particularly in cases where thick masonry walls significantly reduce the reliability of WiFi transmission. For this reason, the communication between LEMS boards

relies on a robust daisy-chain wiring scheme using the MODBUS RS485 protocol, with a commercial data logger acting as the master device.

The use of an Arduino device for each acquisition node was considered unsuitable for long-term environmental monitoring in historic buildings, since Arduino platforms are not designed for continuous operation in harsh or unregulated conditions, nor do they provide the robustness, EMI protection, and communication reliability required for a multi-node RS485 network. Moreover, their form factor and wiring requirements are difficult to integrate discreetly within heritage-protected environments. For these reasons, a dedicated data-acquisition board was developed to meet the specific constraints of this study.

2.1. Liminal Environmental Monitoring System (LEMS) Architecture

Figure 1 shows the data acquisition architecture. Both the hardware and the software of the board can be adapted to the requirements of the selected sensors, allowing a wide range of hygrothermal parameters to be measured using the same compact and low-cost platform. For this study, the boards were configured to acquire all the physical quantities relevant to the scientific investigation. The sensor network was implemented by connecting the boards in a daisy-chain configuration using the MODBUS RTU protocol over an RS485 link, with a 4neXt EasyLogXL-A datalogger acting as the master device. The datalogger periodically polls the sensors and stores the collected data locally on an SD memory card. In addition, a 4G mobile data connection enables data upload to an FTP server and provides remote access for system management. Each board consisted of a Printed Circuit Board (PCB) having two configurable inputs (either analog or digital) and one onboard Inter-Integrated Circuit (I2C) sensor measuring ambient temperature and humidity. Daisy chaining allows the boards to be powered at 24 V using power over ethernet (PoE) approach.

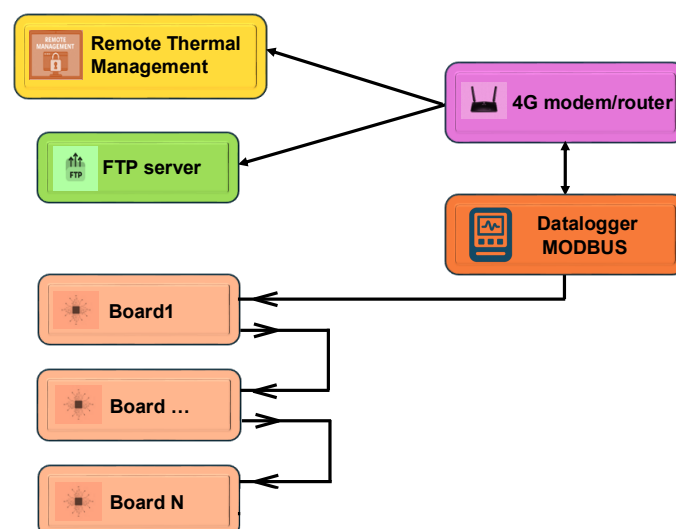


Figure 1. Schematization of the main components of the data acquisition system.

The block diagram of the data acquisition boards is represented in Figure 2. The components on the electronic board are powered at 5 V thanks to a high-efficiency DC-DC converter connected to a π filter. A further low-dropout voltage regulator provides the 3.3 V used in the biasing network of Resistance Temperature Detectors (RTDs). The terminal block used to connect external sensors also provides an auxiliary power input, allowing the board to supply either 5 V or 24 V to external sensors when required. The data acquisition board includes a low-power half-duplex RS-485 transceiver (SP3485EN, MaxLinear Inc., Carlsbad, CA, USA) that enables MODBUS RTU communication with the microcontroller over an RS-485 link. The board is also equipped with two low-voltage, rail-to-rail opera-

tional amplifiers (op-amps): one configured in a non-inverting topology and the other in an inverting topology. In the latter case, the non-inverting input is driven by a buffered digital-to-analog converter (DAC) controlled by the onboard microprocessor. Signals from external sensors can be attenuated using voltage dividers, buffered, or amplified by the op-amps before being routed either to the 10-bit internal analog-to-digital converter (ADC) or to an external 16-bit ADC. A temperature and humidity sensor and an external Electrically Erasable Programmable Read-Only Memory (EEPROM) communicate with the microcontroller directly through a I²C. Different board configurations can be achieved by installing only the components required for a specific application. The configurations utilized for this case study are presented in the following sections.

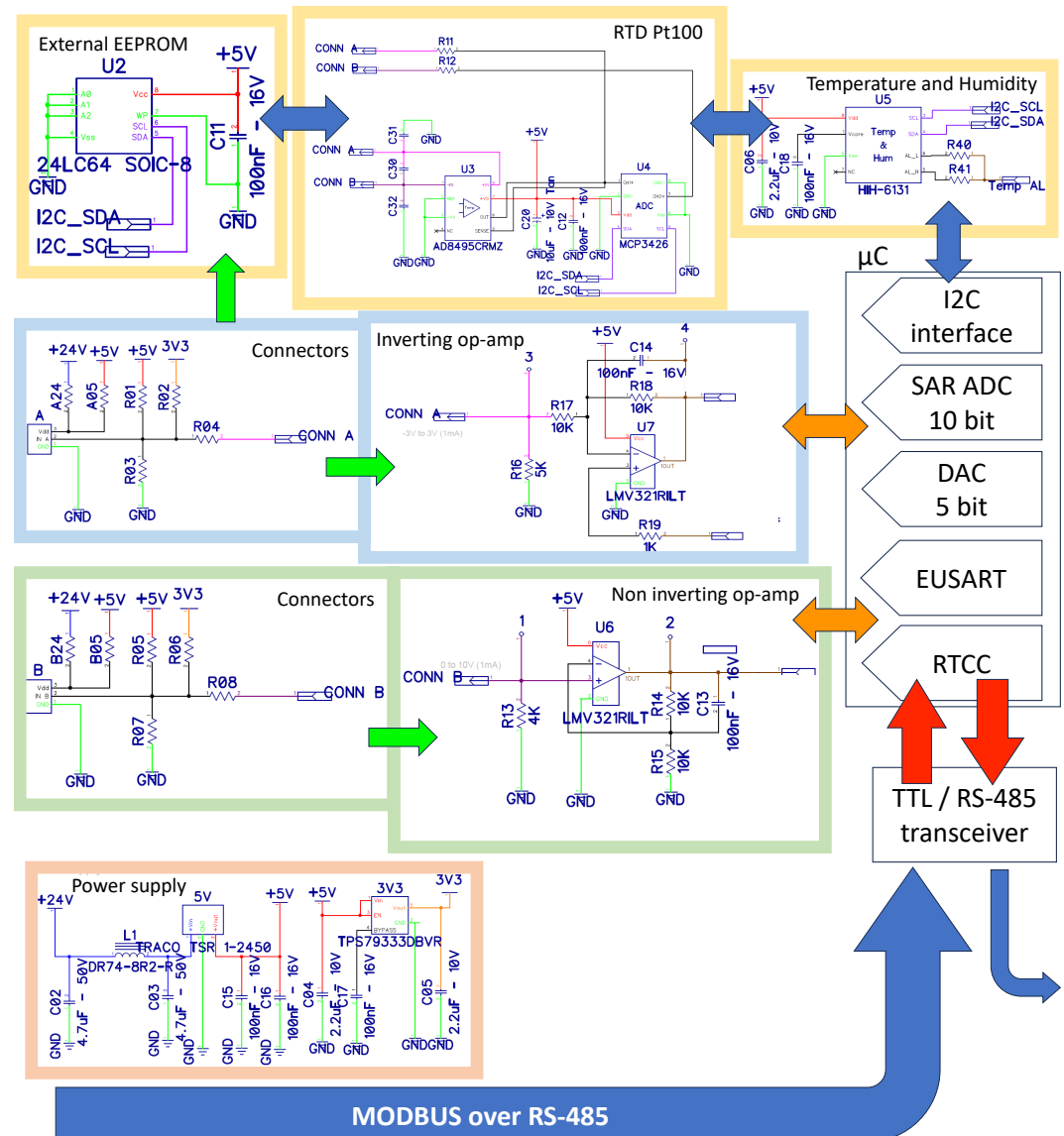


Figure 2. Block diagram of the DAQ boards.

2.2. Monitoring Configurations

2.2.1. Configuration 1: RH, NTC, PYRA

In this configuration, the electronic board was equipped with three main components: an external temperature sensor, a voltage-output pyranometer, and an onboard I²C temperature and humidity sensor. Each component is interfaced through dedicated front-end electronics and connected to an 8-bit microcontroller (Microchip PIC16F1937-

I/PT, Microchip Technology, Chandler, AZ, USA), which manages both data acquisition and communication with the MODBUS master. The architecture of the board is shown in Figure 3. A negative temperature coefficient (NTC) thermistor was used as the external temperature sensor, and it was placed in a voltage divider referenced to 3.3 V. The device was biased through a 27 k Ω resistor, and the voltage divider output was fed to a Microchip MCP3426 (Microchip Technology, Chandler, AZ, USA), which integrates a sigma–delta ADC and a programmable gain amplifier (PGA) with differential input. The MCP3426 measures the voltage drop across the NTC and communicates with the microcontroller via I²C, which then converts the thermistor resistance into the corresponding temperature.

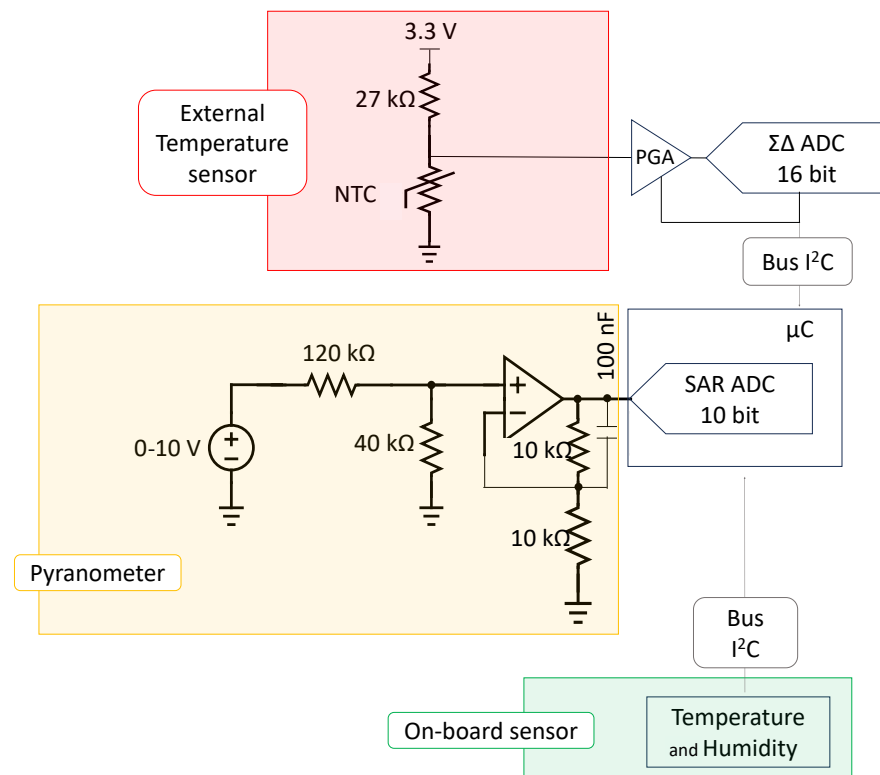


Figure 3. Block diagram of the board configured for the acquisition of temperature and humidity and outdoor light intensity.

The pyranometer (Delta Ohm LPPYRA03, Delta Ohm, Caselle Di Selvazzano, Italy) is a passive sensor with a 0–10 V output and is powered at 24 V directly from the board. Its voltage output was scaled through a voltage divider to match the full-scale input range of the front-end electronics. The conditioned signal was then buffered by an operational amplifier in a non-inverting configuration, and the op-amp output was directly sampled by the microcontroller's 10-bit successive approximation register SAR-type ADC (Microchip PIC16F1937-I/PT). An onboard humidity and temperature sensor (Honeywell HIH6131, Honeywell, Morristown, NJ, USA) communicates with the microcontroller via the I²C protocol.

2.2.2. Configuration 2: NTC, RH, PHOTO

In this configuration, temperature and humidity measurements were provided using the same I²C sensor, but it employs a different front-end electronic design for the external sensors (see Figure 4). The light-detection functionality is based on a silicon photodiode (Osram SFH 206 K, Osram, Munich, Germany) connected to a bandwidth-limited trans-impedance amplifier. The photocurrent generated by direct illumination of the photodiode

was converted into a voltage signal by the transimpedance stage. The non-inverting input of the operational amplifier was connected, through a $1\text{ k}\Omega$ resistor, to the digital-to-analog converter integrated into the microcontroller. This configuration allows the output-signal bias to be adjusted by setting specific holding registers via the MODBUS protocol. Finally, the microcontroller's SAR ADC directly samples a voltage proportional to the light intensity incident on the photodiode.

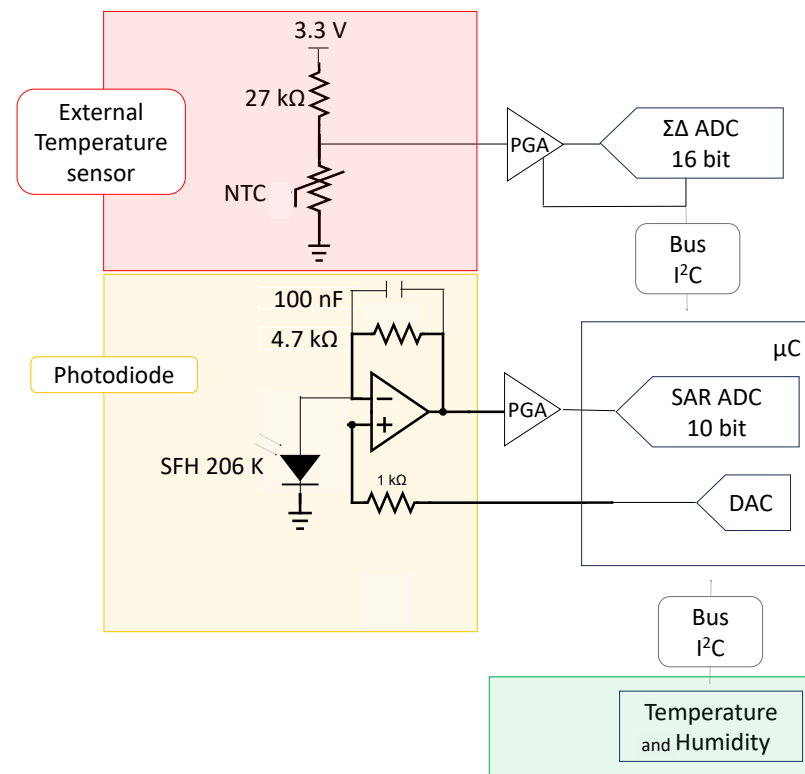


Figure 4. Block diagram of the board configured for the acquisition of temperature, humidity and outdoor light intensity.

2.2.3. Configuration 3: RH, ANEMOMETER

As depicted in Figure 5, this configuration allows the monitoring of wind parameters (intensity and direction), as well as of the ambient temperature and humidity. Wind velocity was measured using an anemometer that provides both a tachometric output for wind speed and a potentiometric output for wind direction. The open-collector tachometric signal was connected to an interrupt-driven GPIO pin, which triggers a 16-bit counter used to determine the pulse frequency corresponding to the wind speed. The potentiometric output of the wind-direction sensor was buffered and then sampled by the microcontroller's 10-bit SAR ADC. As in the previous configurations, temperature and humidity measurements are provided by the Honeywell HIH6131 sensor, which communicates with the microcontroller via the I²C protocol.

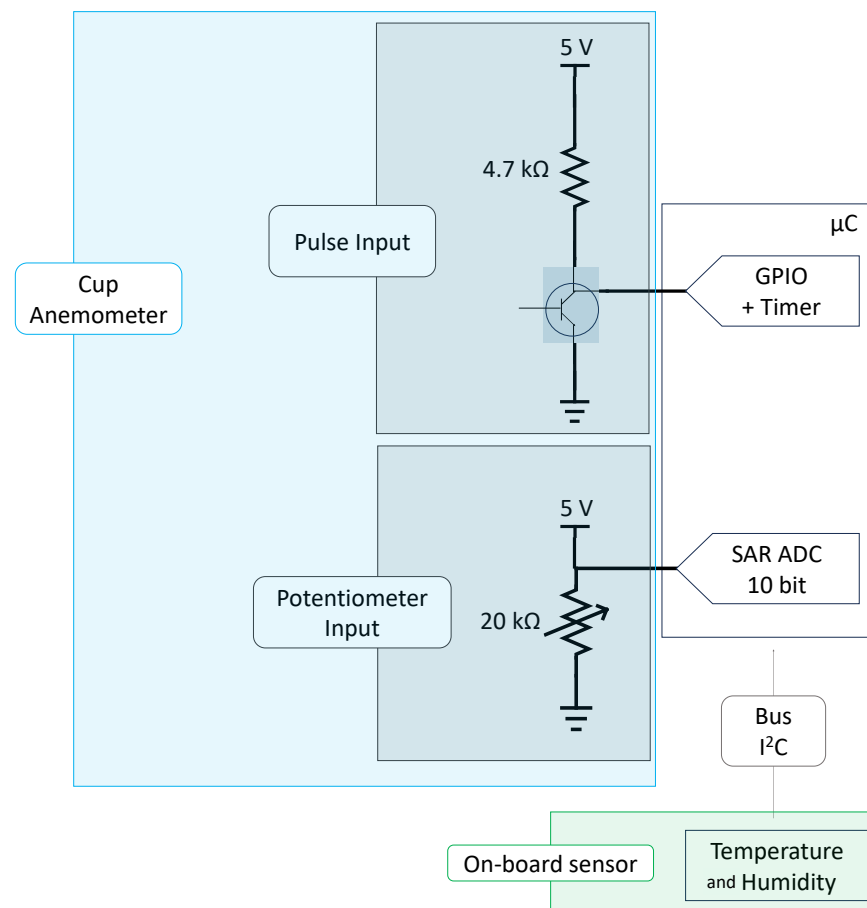


Figure 5. Block diagram of the board configured for the acquisition of temperature, humidity and ambient wind parameters.

2.2.4. Configuration 4: RH, HOT WIRE

In some monitoring locations, the use of a hot-wire anemometer was preferred over a cup anemometer because it offers higher sensitivity at very low wind speeds and a more compact form factor, which is essential when working in spatially constrained areas of historic buildings. Similarly to the previous configuration, this one enables the monitoring of wind velocity using a hot-wire anemometer while also measuring ambient temperature and humidity. The electrical schematic of the board is shown in Figure 6.

The hot-wire anemometer (E+E EE671, E+E Elektronik, Engerwitzdorf, Austria) provides a low-impedance 0–10 V analog output. This signal was attenuated using a voltage divider so that it fits the input range of the front-end electronics. After conditioning, the signal was buffered by an operational amplifier configured in a non-inverting mode, and the resulting voltage was digitized by the microcontroller's ADC. Temperature and humidity measurements were as usually supplied by an onboard Honeywell HIH6131 sensor.

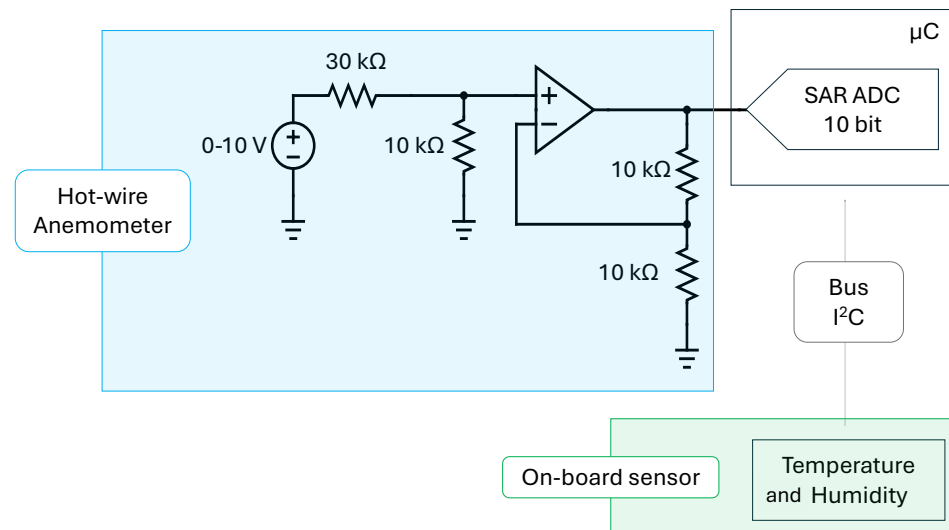


Figure 6. Block diagram of the board configured for the acquisition of temperature and humidity and wind speed in liminal spaces.

2.2.5. Configuration 5: RH, DI

The electrical diagram shown in Figure 7 indicates that, for this configuration, the PCB was modified to accommodate two main sensors: a digital sensor for door/window monitoring and the Honeywell HIH6131 for humidity and temperature measurements. This setup enables the detection of door and window openings and closings, which—knowing their dimensions—can be used to estimate air exchange between the interior and exterior of the building. The sensor mounted on the door frame is a reed switch paired with a magnet attached to the door. When activated, the sensor pulls the output signal to ground, which is normally held at 5 V by a 4.7 kΩ pull-up resistor. This signal is read by the microcontroller's GPIOs. As in the previous configurations, the humidity and temperature sensor communicates with the microcontroller via the I²C protocol.

Table 1 provides a summary of sensors installed in for all the proposed configurations, except for the digital sensor.

Table 1. Sensor handled by the data acquisition system for this case study.

Sensor Type	Manufacturer	Model	Measurement Range	Output Signal	Accuracy	Supplied Voltage
Temperature/RH	Honeywell	HIH-6131	−40 ÷ 125 °C	I ² C	±1.0/±3.0%	5 Vdc
NTC	Vishay	NTCLE413	−40 ÷ 125 °C	Resistance	±3%	-
Pyranometer	Delta OHM	LPPYRA03	0–2000 W/m ²	0–10 V	±30 W/m ^{−2}	24 Vdc
Photodiode	Osram	SFH 206 K	0–250 W/m ²	0–2 mA	5%	-
Cup anemometer	Davis Instruments	6410	0.5–70 m/s	Tachometric	±1 m/s/ ±5% mv *	5 Vdc
			0–360 °	Resistance	±3°	-
Hot-wire anemometer	E+E Elektronik	EE671	0–5 m/s	0–10 V	±0.2 m/s + 3% mv *	24 Vdc
Reed relay	Assemtech	PSB130/30	-	Digital TTL	-	5V

* mv = measured value.

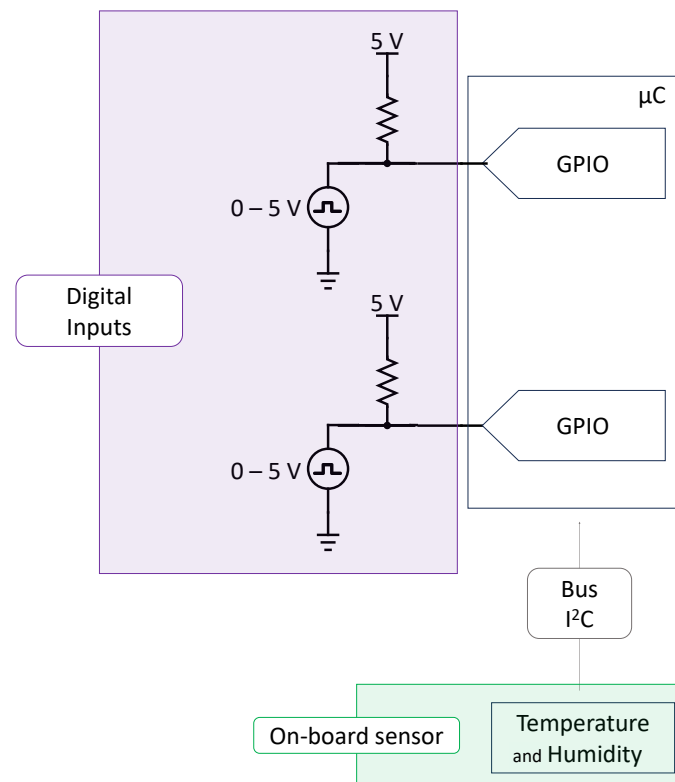


Figure 7. Block diagram of the board configured for the acquisition of temperature, humidity and digital inputs such as door opening.

3. Case Study: Palazzo Costabili

The chosen location for the case study is Palazzo Costabili, built between 1495 and 1504 in Ferrara (FE), Italy (latitude 44.827, longitude 11.627). The fulcrum of the Palazzo is the cloister of honour, completed only on two sides and adorned by a double porches with sculptural decoration in white stone. In addition, the complex presents two loggias with different orientations and several types of outdoor spaces. Palazzo Costabili represents a particularly significant case study for several reasons. It hosts a prestigious national museum, so it fits perfectly into the city's tourist routes. In addition, by virtue of the role enjoyed by the aristocratic family that commissioned it, the building gathers in its architectural configuration important elements of value, including most of the types of transitional spaces that can be found in a historic typical urban fabric. The richness of the case study in term of outdoor and transitional spaces makes it possible, therefore, to study more than one case study at the same time and to verify their relationship to each other, considering the building and the liminal spaces as a complex system in its entirety (and not a series of single elements). The first step of the monitoring campaign was the identification of the best spaces and specific points to be monitored (as shown in Figure 8), in order to accurately map the general environmental behavior of the outdoor spaces of the building.

The interpretation of the irradiance measurements is not straightforward since the radiative environment at the sensor results from a superposition of atmospheric effects (variation in cloud cover and aerosol load) and geometric effects such as shading due to the surrounding facades and arcades. While the first is controlled by meteorological conditions, the latter is governed solely by the 3D geometry of the courtyard and the solar position. In a compact historical building, where the courtyard facades are tall relative to the courtyard, these geometric effects strongly modulate the solar access over the day and year. In the present case study, the irradiance sensor was placed on a totem, whose location is shown in Figure 8, at a position that is directly exposed to the sky only during specific hours. It is

therefore essential to define the local shading that depends only on the building geometry and solar position. To this end, a dedicated solar shading analysis was carried out using optical ray-tracing simulations on a 3D model of the cloister and loggia implemented in TracePro Expert, Lambda research Corporation (Westford, MA, USA) [38].

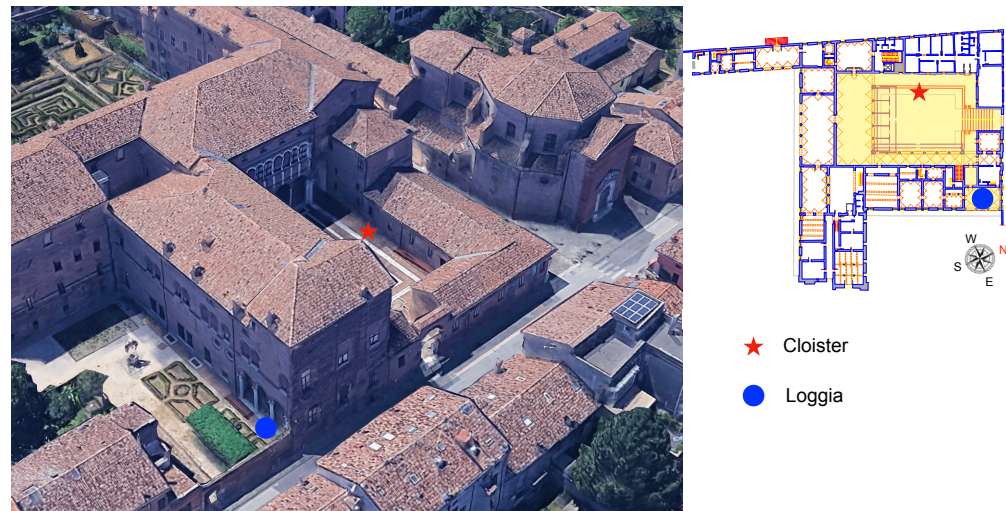


Figure 8. Palazzo Costabili 3D representation and plan cross-section. The star represents the cloister, while the loggia is represented by the blue circle [Google Earth image of Palazzo Costabili, Ferrara. Retrieved 19 November 2025].

The sensors have been divided between the ones dedicated to the monitoring of the cloister and the ones that monitor the loggia. In Figure 9 the schematic representation of the smart-sensor network is provided. The positioning of the sensors was defined according to the following criteria:

- Absence of exceptional external factors that could compromise data collection, such as the presence of heat-emitting machinery or movements that could alter the normal use of the space;
- Height (distance from ground level) as close as possible to human level (to measure the parameters at the point perceived by the user) but still high enough that museum visitors could not interfere with data collection by touching or moving the equipment;
- Principle of reversibility, meaning that the installation of the equipment would not cause damage to the historic structure, strongly required when working on heritage buildings of significant value.

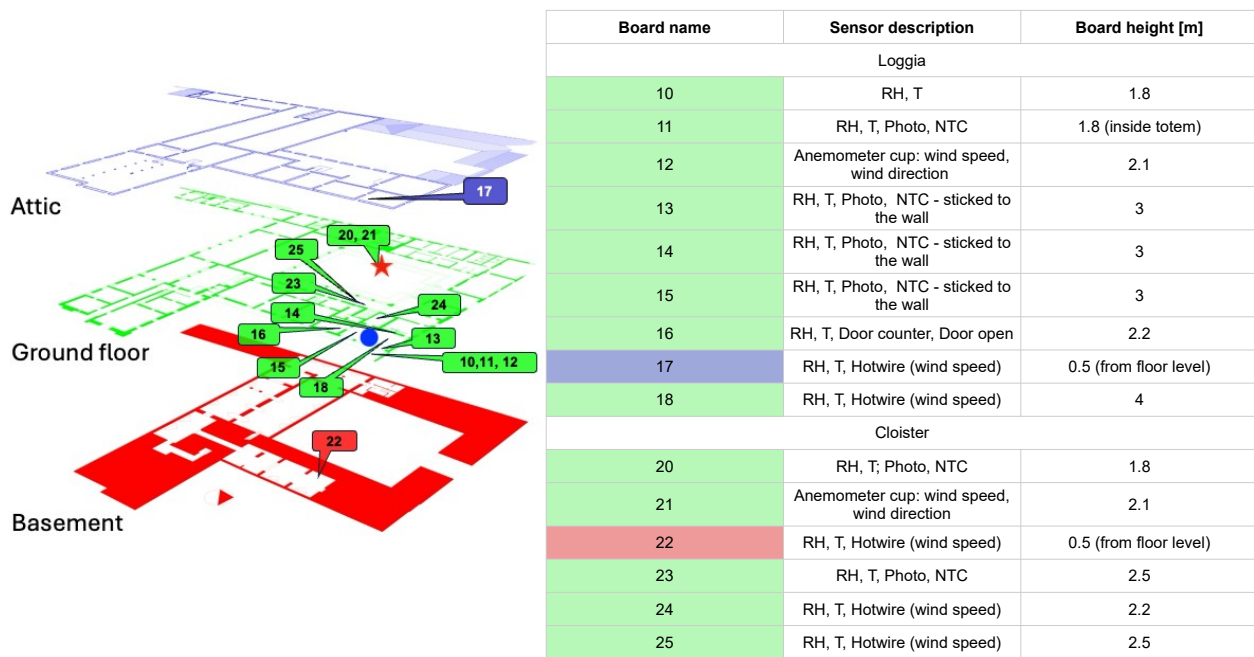


Figure 9. Three-dimensional schematic of the LEMS installation in the three levels of the sensor network (basement, ground floor and attic) where RH is relative humidity and T is temperature.

Figure 10 shows the setup installed at Palazzo Costabili.

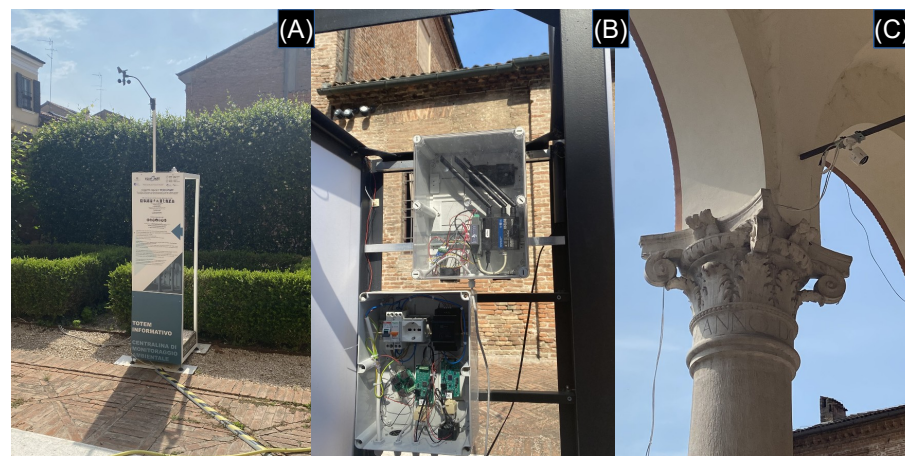


Figure 10. LEMS network installed at Palazzo Costabili: (A) Totem placed outside the loggia. (B) Board inside the totem installed in the cloister. (C) Sensors installed in the loggia.

4. Results

4.1. Board Calibration

The most significant sources of error in measurement systems include sensor errors, transducer errors, converter errors, and signal transmission errors [39]. For the reasons stated at the end of Section 1, the used sensors are assumed to be factory-calibrated. Indeed, the values measured by the system were compared with reference ones. For hygrothermal parameters the reference used was a “DataTaker DT80” coupled with similar physical sensors, whereas for the irradiance measurements “FLUKE IRR1-SOL” was employed. The sensors coupled to both the LEMS and DT80 were subjected to the same external conditions, and the data measured by the former were compared to the one collected by the latter to calibrate the LEMS boards using a correction function. The temperature sensors

were calibrated by placing them inside a climatic chamber and increasing the ambient temperature in 5 °C steps over the range from −10 °C to 70 °C. This range was chosen as a reasonable full-scale input, reflecting the typical operating conditions expected for the boards in Ferrara. The transient data collected during the temperature ramps was eliminated so that the calibration was based on steady-state data in each step. A similar procedure was used for the calibration of the humidity sensor; however, the considered range was between 20% and 80% with a step of 10%. Humidity levels above 80% RH are typically associated with dew formation or condensation, regimes that lie outside the intended operational conditions of the sensor. For this reason, the calibration focused on the non-condensing range of 20–80% RH. The photodiodes were instead calibrated by comparing the photocurrent values measured by the transimpedance amplifiers with the ones registered by a “FLUKE IRR1-SOL” when exposed to the same irradiance levels. Using a linear curve fitting approach [32], calibration constants that compensate measurement error of LEMS for the different sensors can be provided. Figure 11 shows the calibration function, which correlates the data acquired with the two data acquisition systems.

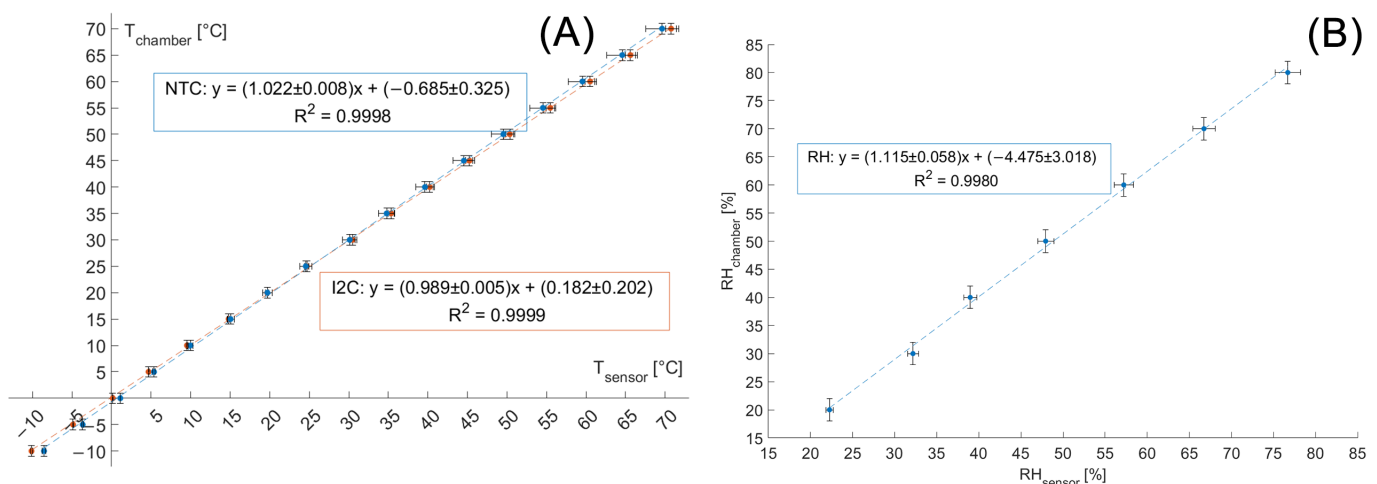


Figure 11. Correlation between measurements performed by the sensor and the same physical quantity imposed in a controlled environment: (A) temperature (in orange the I²C sensor, in blue the NTC sensor) (B) relative humidity.

The irradiance sensors were configured with two distinct full-scale input ranges. The high-range setting ($>600 \text{ W m}^{-2}$) is intended for measurements under direct solar exposure, whereas the low-range setting ($\leq 600 \text{ W m}^{-2}$) is designed for operation in shaded or low-irradiance conditions. The improvement in both the maximum and the average measurement due to the calibration constants implementation is reported in Table 2.

Table 2. Measurement accuracy improvement after the calibration procedure.

Sensor	Uncalibrated LEMS		Calibrated LEMS	
	Maximum Error	Average Error	Maximum Error	Average Error
I2C temperature sensor	0.7 °C	0.4 °C	0.5 °C	0.2 °C
NTC temperature sensor	1.7 °C	0.5 °C	0.8 °C	0.3 °C
I2C humidity sensor	3.3%	2.4%	1.4%	0.8%
Photodiode	126 W/m ²	26 W/m ²	70 W/m ²	12 W/m ²

4.2. Shading Simulations

The model was focused on those elements that control solar access in the cloister and loggia, namely, internal facades, arcade and roof overhangs. The interior room and

not-visible part were omitted as they do not affect the shading at the measurement point. The simulations were run with the Solar Emulator tool of TracePro Expert (version 25.4), using 2×10^7 rays at each sun position, with the goal to obtain the global horizontal irradiance (GHI) in clear sky conditions. The raytracing simulations are used to discriminate if sudden variations in the measured irradiances are due to cloud cover effects or shadowing by surrounding buildings.

As shown in Figure 12, the geometric model reproduces the overall plan dimensions of the cloister and loggia, the horizon shading caused by surrounding buildings, and the main architectural features that cast significant shadows, such as columns, arcades, and cornices. The façade profiles were reconstructed from 2D views of the building, achieving a good balance between geometric accuracy and computational efficiency. The model was oriented with respect to true North based on site surveys, so that the solar azimuth and altitude angles could be consistently applied for a given date and time. This approach is in accordance with shading analyses adopted in buildings and urban solar simulations [40]. Figure 13 and Figure 14 represent the result of the optical shading simulations in the cloister and in the loggia, respectively.

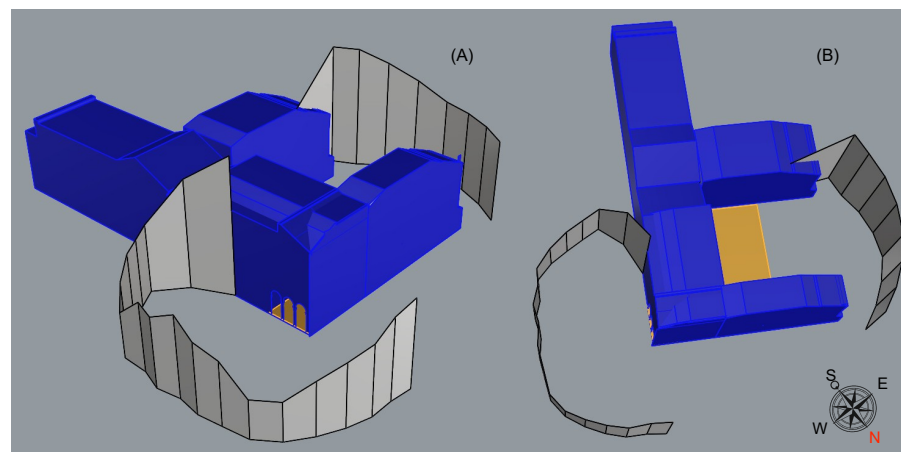


Figure 12. Three-dimensional model for the optical simulation: (A) The loggia seen from the outside. (B) The cloister seen from above. For both images, the yellow region represents the floor and the color blue highlights Palazzo Costabili.

In mid-July (Figure 13), the cloister is exposed to direct sunlight from 10 a.m. to 5 p.m. The radiant power reaching the cloister floor is influenced both by the shading produced by the surrounding buildings and façades and by variations in clear-sky irradiance. The direct sunlight incident on the cloister floor contributes significantly to overheating in this area compared with the shaded portions of the building. In Figure 13, the star indicates the location of the totem that hosts the weather station and the PC supervisor (MODBUS master).

Figure 14 shows the corresponding pattern of direct sunlight on the loggia floor. Due to the orientation of the loggia and the arrangement of the surrounding buildings, direct sunlight reaches the loggia only in the morning; after 12 p.m., the radiant power drops sharply.

4.3. Microclimate Conditions in the Cloister and Loggia

Every hour two CSV files (one for the cloister and one for the loggia) are created in which all the sensors of the corresponding group record their data minute by minute. Every file is stored on a local computer and also backed up on a FTP server. The folder structure follows a hierarchical organization, consisting of the root directory, followed by year and month subfolders, which contain the hourly CSV files. All data acquired are

aggregated using a MATLAB code, which collects all the minute-based data of a given year in a single CSV file. The aggregated data can then be more easily handled by the analyzer MATLAB script to be read and analyzed. As an example, Figure 15 reports the 2-minutes moving mean of the temperatures and irradiances measured in the cloister and in the loggia between the days of 12 July and 15 July 2022.

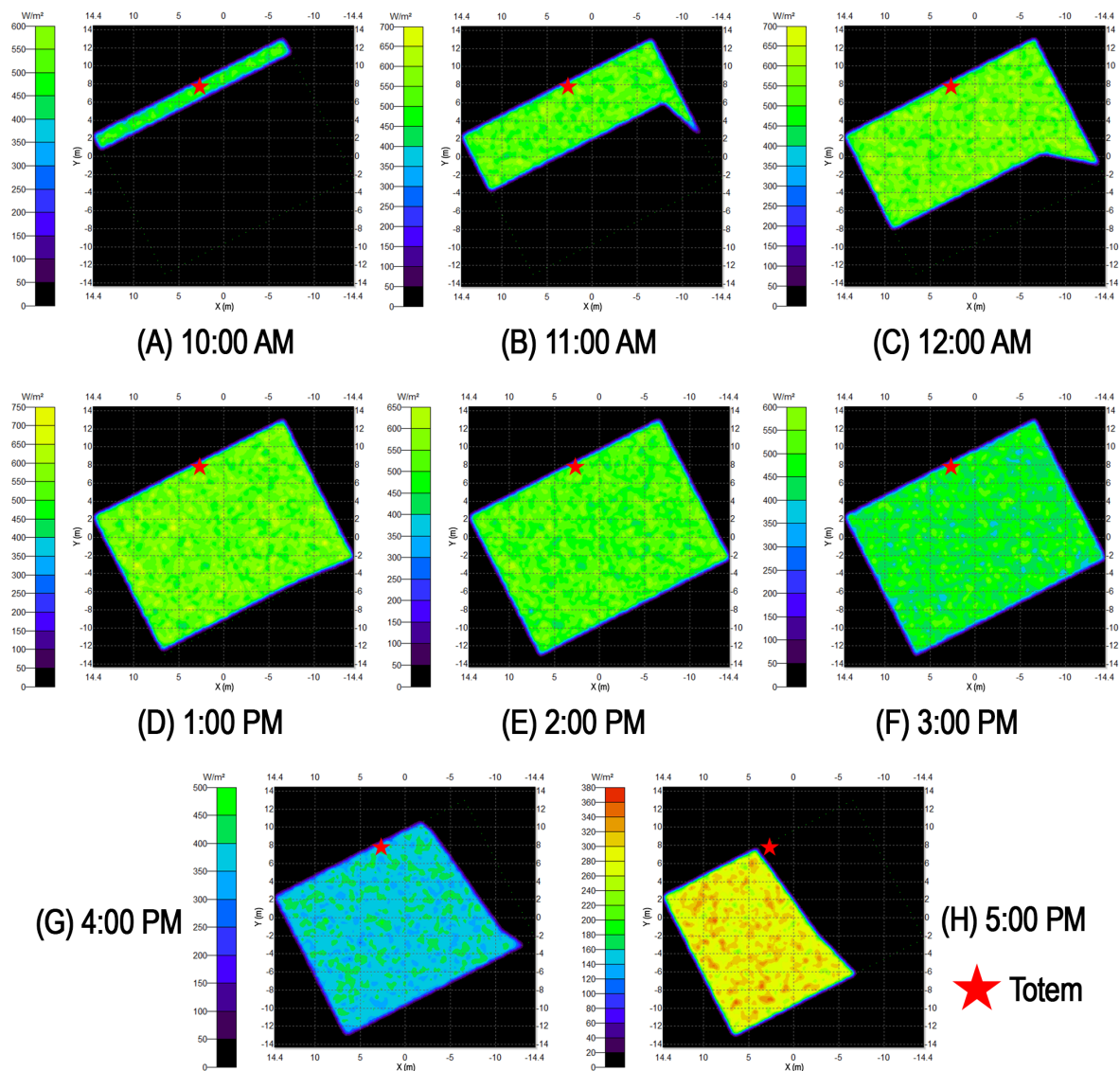


Figure 13. Cloister shading optical simulations of 13 July from 10 a.m. to 5 p.m.

The board 20 NTC shows a considerably higher temperature compared to the other cloister sensors, in accordance with the fact that the totem is under direct sunlight for many hours of the day. The NTC itself is not directly illuminated as it is shaded by the totem's side panels. In turn, the side panels might be limiting convective heat exchange inside, leading to some overestimation in the temperature. The moments in which the totems go from shade to direct sunlight and vice versa are denoted by the sharp increase and decrease in the irradiance profiles. On board 23, the temperature sensor has a sharp peak around the 6:30 p.m. mark, a time in which the Sun's height and angle are such that the board is directly illuminated. T sensors are surface-mounted (SM) components coated in black, which have the drawback of being highly susceptible to direct illumination, leading to unreliable measurements under this condition. It can be observed that this sharp and quick increase in temperature is less prominent in the NTC of the same board, as the NTC is not as

strongly influenced by direct illumination and its placement also allows for a more efficient convective heat transfer with the surrounding air. In the loggia the considered temperatures follow very similar profiles, with board 18 showing slightly higher values during daytime (which can be ascribed to air stratification effects). The uncertainties on these measurements are the ones reported in Table 1. From these data, the Temperature–Humidity–Sun–Wind index (THSW) has been calculated for the points in which the considered boards were mounted. The THSW under direct illumination is defined, according to [41], as follows:

$$\text{THSW} = -1.8 + 1.07T + 2.4P - 0.92v + 0.044Q_g \quad (1)$$

where T is the temperature [$^{\circ}\text{C}$], P is the vapor pressure [kPa], v the wind speed [m/s] and Q_g is the irradiance corrected by the average amount of a person surface area exposed to the sun (defined as $Q/6$, with Q =irradiance [W m^{-2}]). In shaded areas the THSW definition becomes the following:

$$\text{THSW} = -2.7 + 1.04T + 2.0P - 0.65v \quad (2)$$

The THSW values are plotted in Figure 16.

A moving averaged over a 2-minute interval and a Savitzky–Golay filter have been applied to the THSW profiles to attenuate the effect of quick fluctuations in the measured values. The THSWs act as a “perceived temperature” and quantify the amount of comfort experienced by a person standing near the considered sensor boards, with lower THSWs corresponding to a higher degree of comfort (at least up to a certain threshold). The data suggests that the shade and air current generated by the liminal spaces of the cloister has a positive effect on the THSWs, creating a more pleasant microclimate than the one present in open spaces. This is especially true in the atrium where board 24 is placed, in which the THSW has a minimum in the morning, slowly increasing throughout the rest of the day and then reaching a constant value in the evening/night, compared to board 11 which instead has its maximum around midday and the afternoon. In the loggia, the THSWs show that for the first day (cloudy weather) higher thermal comfort was achieved in the open area, while for the subsequent two days the peak THSWs are similar between the location of board 11 (totem) and board 14. The board 18 spot would be the one of highest discomfort, again due to air stratification effects. Stratification effects also play a role, albeit a less prominent one, in the temperature/THSW of board 14, as it was placed on the inner wall of the loggia but at the same height of board 18. The relative uncertainties on the calculated THSWs are reported in Table 3.

Table 3. Relative uncertainty on the calculated THSWs obtained by propagating the uncertainties on each sensor measurement.

Board	Relative Uncertainty [%]
20 (NTC)	$\pm(2 \div 5)$
23 (T)	$\sim \pm 1$
23 (NTC)	$\pm(2 \div 3)$
24 (T)	$\sim \pm 1$
11 (NTC)	$\pm(3 \div 11)$
14 (NTC)	$\pm(2 \div 3)$
18 (T)	$\sim \pm 1$

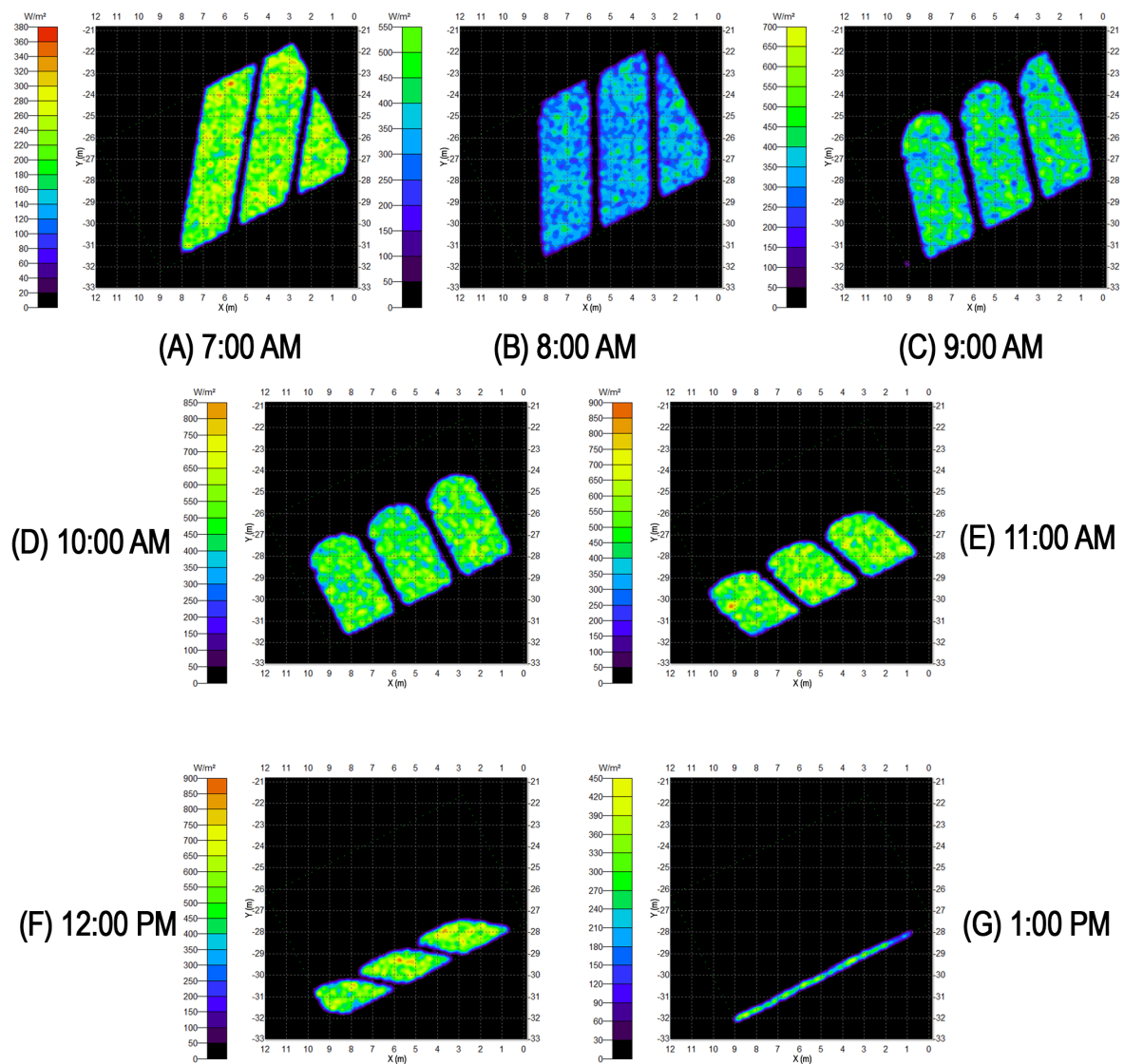


Figure 14. Loggia shading optical simulations of 13 July from 7 am to 1 pm.

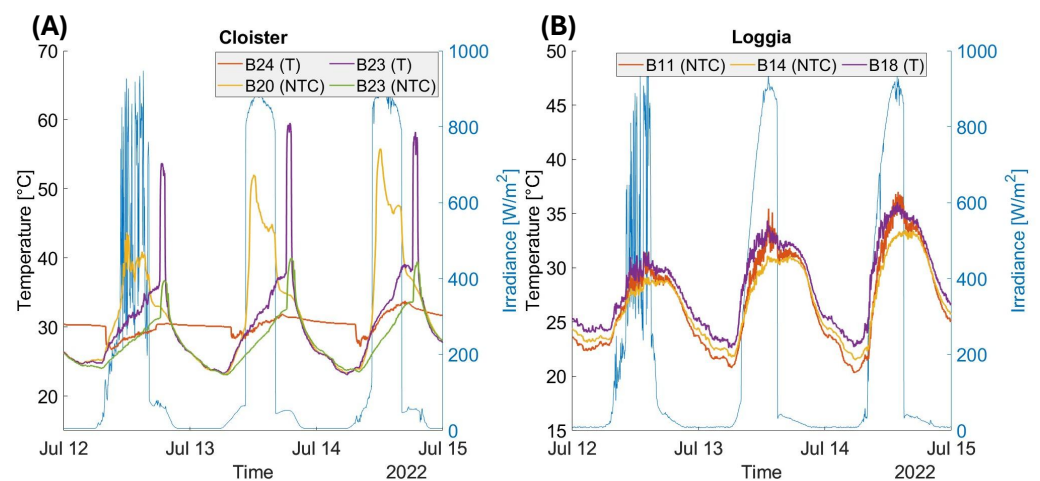


Figure 15. (A) Temperature measured by boards 20, 24 and 23, along with the irradiance measured by the cloister totem (board 20). (B) Temperatures measured by boards 11, 14, and 18, along with the irradiance measured by the loggia totem (board 11).

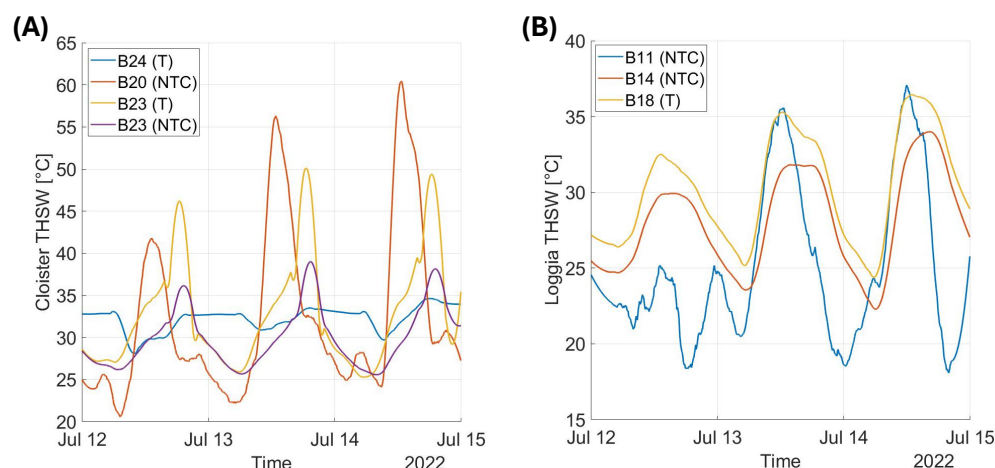


Figure 16. (A) Temperature measured by boards 20, 24 and 23, along with the irradiance measured by the cloister totem (board 20). (B) Temperatures measured by boards 11, 14, and 18, along with the irradiance measured by the loggia totem (board 11).

A definitive and complete analysis of the data collected during the 4 years monitoring of the museum is beyond the scope of this paper and will be analyzed and reported in the future. However, thermal data of the example days considered seems to be consistent with the results of similar works found in the literature, such as Watanabe et al. [42]. In their work, the authors evaluated the mean perceived temperature value in shaded areas during summer in a humid subtropical region using the Universal Effective Temperature (ETU) index, finding a value of 28.4 °C in building shade and 30.6 °C in pergola shade.

5. Discussion: Lesson Learned, Further Development and Smart-City Implications

The LEMS exhibited robust performance in this case study, yet several aspects could still be enhanced. A primary limitation is that the current boards require wired power connections and physical access for firmware updates. Moreover, most system downtime was caused by faulty connectors or degradation of data cables, particularly when exposed to outdoor or harsh environments. To mitigate these issues, future developments will focus on implementing solar powered battery charging systems and reducing overall power consumption, with the long-term goal of integrating long-range wireless communication capabilities. These improvements would enhance system flexibility, simplify installation, and extend applicability to locations where wired connections are impractical. To facilitate wider usability, particularly for non-expert users, future versions may also incorporate optional support for low-cost single-board computers such as the Panda Board, Raspberry Pi, or Arduino platforms. While the PIC-based custom hardware remains preferable for deterministic, low-power, and long-term monitoring, these complementary platforms could provide user-friendly interfaces or embedded wireless sensor network capabilities, as demonstrated in several related studies [32,33,43]. Additional improvements are envisioned at the hardware sensing layer. The integration of further environmental sensors, e.g., for acoustic performance, CO₂, VOCs, PM_{2.5}, PM₁₀, and occupancy, would enable a more comprehensive assessment of indoor environmental quality. At the software level, future work will focus on developing a graphical user interface (GUI) that enables end users to configure each board without any programming knowledge once the hardware setup is defined. Moreover, integrating next-generation LEMS units with secure communication and execution environments would open the possibility of real-time data analysis, evaluation of thermal comfort using combined indices (as suggested by ASHRAE Standard 55), and optimization of Heating, Ventilation, and Air Conditioning (HVAC) systems using

machine learning or neural network approaches. Such methodologies could further be extended to occupancy recognition and energy-use reduction strategies. Finally, additional cost reductions may be achieved by incorporating low-cost environmental sensors where appropriate, thereby supporting wider deployment of the system.

The coupling of in-situ monitoring with 3D raytracing simulations could represent a stepping stone towards more accurate predictions and evaluations of heritage buildings. In future works, this coupling could also be further strengthened by employing neural networks and machine learning models [44,45], allowing to include other physical quantities besides solar irradiance and allowing more quantitative conclusions to be derived. With the approach presented in this work, monitoring more than one heritage building in the same city would open the possibility to cross-correlate simulations and measurements across the building “network” and to move towards an urban-scale environmental digital twin.

6. Conclusions

This paper has presented the Liminal Environmental Monitoring System (LEMS), a novel data acquisition system designed specifically for monitoring environmental conditions in liminal spaces in historic buildings and demonstrated its applications in a cloister and loggia embedded in a dense historic urban fabric. The system prioritizes flexibility and affordability while adhering to heritage building conservation constraints, which is achieved through the use of low-impact sensors and a compact design minimizing aesthetic disruption. It combines a flexible, modular data acquisition board with robust wired communication and a commercial datalogger, ensuring compatibility with the constraints of heritage environments while maintaining scalability and integration potential within broader smart-city infrastructures. The LEMS architecture leverages a master–slave configuration for the data acquisition and user-defined storage intervals, managing multi-parameter environmental data, such as air temperature, relative humidity and solar irradiance. Redundancy was ensured through the positioning of multiple sensor boards registering similar physical parameters. Data availability was guaranteed through a 4G modem. From a microclimate perspective, this case study at Palazzo Costabili in Ferrara demonstrated the relevance of monitoring in representative liminal spaces of historic city centers. To interpret the irradiance signal, a dedicated optical model was implemented to distinguish shading due to purely geometric effects. This enables a more robust interpretation of irradiance, identifying periods when reductions in measured irradiance were attributable to facade shading rather than cloud passage. The combined measurement–simulation approach effectively operates as a micro-digital twin of the liminal space, capturing the interplay between measured irradiance and the geometric configuration of surrounding architectural elements. By simulating local shading patterns and temporal variability, this micro-digital twin enables more accurate attribution of irradiance reductions and supports scenario testing under different solar or architectural conditions. As such, it provides a robust and transferable methodological framework that can be applied to other courtyards, loggias, and semi-outdoor environments typical of historic urban fabrics and that can be coupled to policy-making and place-making approaches and methodologies. The LEMS’s adaptability and minimal footprint make it suitable for a wide range of heritage building applications across diverse geographical and climatic conditions, especially if wireless capability and low power consumption will be included. In the context of smart heritage, the proposed architecture and workflow contribute to filling the gap in the monitoring of liminal spaces, since they play an important role in regulating microclimates, supporting outdoor comfort for residents and visitors and influencing the conservation state of surrounding building elements. The LEMS demonstrated that it is feasible to deploy a dedicated, heritage-compatible monitoring layer in these spaces, obtaining high-resolution monitoring data

that can improve the energy efficiency and conservation of historical buildings. A dedicated paper will be presented in the future providing the analysis of the collected monitoring data; however, the preliminary results presented here demonstrate the potential of LEMS's data to evaluate the impact of transitional spaces as well as the flexibility of the presented setup and the valuable coupling of simulations and sensing as a stepping stone towards city-scale digital twins.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/smartcities9010014/s1>, In the .zip folder attached there are three files: Aggregated_Loggia.xlsx, Aggregated_Portico.xlsx and Readme.txt. The .xlsx files contain all the raw sensor data collected between 12 July 2022 and 15 July 2022. The first two digits of each column name represent the board that collected that data and the last part of the name represents the specific sensor reported in that column. This explanation is included in the Readme.txt file.

Author Contributions: Conceptualization, G.M., M.C., V.M. and P.D.; methodology, V.D. and G.M.; software, D.V. and L.S.; validation, D.V., L.S., V.D. and N.A.; formal analysis, L.S. and V.D.; investigation, G.M., D.B. and D.V.; resources, D.V.; data curation, V.D. and L.S.; writing—original draft preparation, G.M.; writing—review and editing, V.D., L.S. and D.V.; visualization, L.S. and N.A.; supervision, D.V.; project administration, P.D.; funding acquisition, P.D. All authors have read and agreed to the published version of the manuscript.

Funding: The results presented in this paper are part of the PRIN 2017 “TECH START—key enabling TECHNOlogies and Smart environmenT in the Age of gReen economy. Convergent innovations in the open space/building system for cli- maTe mitigation”, P.I. M. Losasso, UO: CNR Roma, PoliTo, UniFe, UniNa, Roma Tre, Roma La Sapienza. The project has received funding from the Italian “Ministero dell’Istruzione e del Merito”, “Programma PRIN—Progetti di ricerca di Rilevante Interesse Nazionale”.

Data Availability Statement: The data presented in this study are available in the Supplementary Materials.

Acknowledgments: During the preparation of this study, the authors used Chat GPT 5.0 for improving the manuscript readability. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ADC	Analog-to-Digital Converter
DAC	Digital-to-Analog Converter
EEPROM	Electrically Erasable Programmable Read-Only Memory
ETU	Universal Effective Temperature
GHI	Global Horizontal Irradiance
GUI	Graphical User Interface
HVAC	Heating, Ventilation, and Air Conditioning
I2C	Inter-Integrated Circuit
IoT	Internet of Things
LEMS	Liminal Environmental Monitoring System
NTC	Negative Temperature Coefficient
PCB	Printed Circuit Board
PGA	Programmable Gain Amplifier
PoE	Power over Ethernet
RH	Relative Humidity
RTD	Resistance Temperature Detector

SM Surface-Mounted
THSW Temperature Humidity Sun Wind

References

1. Cacciotti, R.; Kaiser, A.; Sardella, A.; De Nuntiis, P.; Drdác, M.; Hanus, C.; Bonazza, A. Climate change-induced disasters and cultural heritage: Optimizing management strategies in Central Europe. *Clim. Risk Manag.* **2021**, *32*, 100301.
2. Buda, A.; de Place Hansen, E.J.; Rieser, A.; Giancola, E.; Pracchi, V.N.; Mauri, S.; Marincioni, V.; Gori, V.; Fouseki, K.; Polo López, C.S.; et al. Conservation-compatible retrofit solutions in historic buildings: An integrated approach. *Sustainability* **2021**, *13*, 2927.
3. Andreotti, M.; Calzolari, M.; Davoli, P.; Dias Pereira, L.; Lucchi, E.; Malaguti, R. Design and construction of a new metering hot box for the in situ hygrothermal measurement in dynamic conditions of historic masonries. *Energies* **2020**, *13*, 2950.
4. Andreotti, M.; Calzolari, M.; Davoli, P.; Pereira, L.D. Hygrothermal performance of an internally insulated masonry wall: Experimentations without a vapour barrier in a historic Italian Palazzo. *Energy Build.* **2022**, *260*, 111896.
5. Mangherini, G.; Diolaiti, V.; Bernardoni, P.; Andreoli, A.; Vincenzi, D. Review of façade photovoltaic solutions for less energy-hungry buildings. *Energies* **2023**, *16*, 6901.
6. Batchelor, D.; Schnabel, M.A.; Dudding, M. Smart heritage: Defining the discourse. *Heritage* **2021**, *4*, 1005–1015.
7. Bernardoni, P.; Mangherini, G.; Gjestila, M.; Andreoli, A.; Vincenzi, D. Performance Optimization of Luminescent Solar Concentrators under Several Shading Conditions. *Energies* **2021**, *14*, 816, 2021.
8. Mangherini, G.; Bernardoni, P.; Baccega, E.; Andreoli, A.; Diolaiti, V.; Vincenzi, D. Design of a ventilated façade integrating a luminescent solar concentrator photovoltaic panel. *Sustainability* **2023**, *15*, 9146.
9. Rajapaksha, I.; Nagai, H.; Okumiya, M. A ventilated courtyard as a passive cooling strategy in the warm humid tropics. *Renew. Energy* **2003**, *28*, 1755–1778.
10. Baboli, F.B.M.; Ibrahim, N.; Sharif, D.M. Design characteristics and adaptive role of the traditional courtyard houses in the moderate climate of Iran. *Procedia-Soc. Behav. Sci.* **2015**, *201*, 213–223.
11. Chun, C.; Kwok, A.; Tamura, A. Thermal comfort in transitional spaces—Basic concepts: Literature review and trial measurement. *Build. Environ.* **2004**, *39*, 1187–1192.
12. Zuo, J.; Daniel, L.; Soebarto, V. Re-Thinking the Role of Urban in-between Spaces. In Proceeding of the 50th International Conference of the Architectural Science Association, Adelaide, Australia, 7–9 December 2016; pp. 7–9.
13. Langevin, J.; Wen, J.; Gurian, P.L. Simulating the human-building interaction: Development and validation of an agent-based model of office occupant behaviors. *Build. Environ.* **2015**, *88*, 27–45.
14. Basto, C.; Pelà, L.; Chacón, R. Open-source digital technologies for low-cost monitoring of historical constructions. *J. Cult. Herit.* **2017**, *25*, 31–40.
15. Kang, S.; Ou, D.; Mak, C.M. The impact of indoor environmental quality on work productivity in university open-plan research offices. *Build. Environ.* **2017**, *124*, 78–89.
16. Nasrollahi, N.; Hatami, Z.; Taleghani, M. Development of outdoor thermal comfort model for tourists in urban historical areas; A case study in Isfahan. *Build. Environ.* **2017**, *125*, 356–372.
17. Evola, G.; Costanzo, V.; Magri, C.; Margani, G.; Marletta, L.; Naboni, E. A novel comprehensive workflow for modelling outdoor thermal comfort and energy demand in urban canyons: Results and critical issues. *Energy Build.* **2020**, *216*, 109946.
18. de la Paz Diulio, M.; Mercader-Moyano, P.; Gómez, A.F. The influence of the envelope in the preventive conservation of books and paper records. Case study: Libraries and archives in La Plata, Argentina. *Energy Build.* **2019**, *183*, 727–738.
19. Caratelli, A.; Siani, A.M.; Casale, G.R.; Paravicini, A.; Fiore, K.H.; Camuffo, D. Stucco panels of Room VI in the Galleria Borghese (Rome): Physical–chemical analysis and microclimate characterization. *Energy Build.* **2013**, *61*, 133–139.
20. Vuerich, E.; Malaspina, F.; Barazutti, M.; Georgiadis, T.; Nardino, M. Indoor measurements of microclimate variables and ozone in the church of San Vincenzo (Monastery of Bassano Romano—Italy): A pilot study. *Microchem. J.* **2008**, *88*, 218–223.
21. Samek, L.; De Maeyer-Worobiec, A.; Spolnik, Z.; Bencs, L.; Kontozova, V.; Bratasz, Ł.; Kozłowski, R.; Van Grieken, R. The impact of electric overhead radiant heating on the indoor environment of historic churches. *J. Cult. Herit.* **2007**, *8*, 361–369.
22. Camuffo, D.; Pagan, E.; Rissanen, S.; Bratasz, Ł.; Kozłowski, R.; Camuffo, M.; della Valle, A. An advanced church heating system favourable to artworks: A contribution to European standardisation. *J. Cult. Herit.* **2010**, *11*, 205–219.
23. Bertolin, C.; Luciani, A.; Valisi, L.; Camuffo, D.; Landi, A.; Del Curto, D. Laboratory tests for the evaluation of the heat distribution efficiency of the Friendly-Heating heaters. *Energy Build.* **2015**, *107*, 319–328.
24. Kramer, R.; van Schijndel, J.; Schellen, H. Dynamic setpoint control for museum indoor climate conditioning integrating collection and comfort requirements: Development and energy impact for Europe. *Build. Environ.* **2017**, *118*, 14–31.
25. Muñoz-González, C.M.; León-Rodríguez, A.; Campano-Laborda, M.; Teeling, C.; Baglioni, R. The assessment of environmental conditioning techniques and their energy performance in historic churches located in Mediterranean climate. *J. Cult. Herit.* **2018**, *34*, 74–82.

26. Canan, F.; Golasi, I.; Falasca, S.; Salata, F. Outdoor thermal perception and comfort conditions in the Köppen-Geiger climate category BSk. One-year field survey and measurement campaign in Konya, Turkey. *Sci. Total Environ.* **2020**, *738*, 140295.
27. Chen, X.; Xue, P.; Liu, L.; Gao, L.; Liu, J. Outdoor thermal comfort and adaptation in severe cold area: A longitudinal survey in Harbin, China. *Build. Environ.* **2018**, *143*, 548–560.
28. Xiao, F.; Fan, C. Data mining in building automation system for improving building operational performance. *Energy Build.* **2014**, *75*, 109–118.
29. Hernández-Morales, C.A.; Luna-Rivera, J.; Perez-Jimenez, R. Design and deployment of a practical IoT-based monitoring system for protected cultivations. *Comput. Commun.* **2022**, *186*, 51–64.
30. Tse, W.L.; Chan, W.L. A distributed sensor network for measurement of human thermal comfort feelings. *Sens. Actuators A Phys.* **2008**, *144*, 394–402.
31. Silva, H.E.; Coelho, G.B.; Henriques, F.M. Climate monitoring in World Heritage List buildings with low-cost data loggers: The case of the Jerónimos Monastery in Lisbon (Portugal). *J. Build. Eng.* **2020**, *28*, 101029.
32. Karami, M.; McMorrough, G.V.; Wang, L. Continuous monitoring of indoor environmental quality using an Arduino-based data acquisition system. *J. Build. Eng.* **2018**, *19*, 412–419.
33. Ali, A.S.; Zanzinger, Z.; Debose, D.; Stephens, B. Open Source Building Science Sensors (OSBSS): A low-cost Arduino-based platform for long-term indoor environmental data collection. *Build. Environ.* **2016**, *100*, 114–126.
34. Angelakoglou, K.; Nikolopoulos, N.; Giourka, P.; Svensson, I.L.; Tsarchopoulos, P.; Tryferidis, A.; Tzovaras, D. A Methodological Framework for the Selection of Key Performance Indicators to Assess Smart City Solutions. *Smart Cities* **2019**, *2*, 269–306. <https://doi.org/10.3390/smartcities2020018>.
35. Angelakoglou, K.; Kourtzanidis, K.; Giourka, P.; Apostolopoulos, V.; Nikolopoulos, N.; Kantorovitch, J. From a Comprehensive Pool to a Project-Specific List of Key Performance Indicators for Monitoring the Positive Energy Transition of Smart Cities—An Experience-Based Approach. *Smart Cities* **2020**, *3*, 705–735. <https://doi.org/10.3390/smartcities3030036>.
36. Du, J.; Yu, Z.; Cheng, S.; Li, L.; Miao, C. Exploring the role of government-driven culture-led micro-regeneration in shaping the sense of place within urban historic districts in China. *Cities* **2026**, *169*, 106575. <https://doi.org/10.1016/j.cities.2025.106575>.
37. Tousi, E.; Pancholi, S.; Rashid, M.M.; Khoo, C.K. Integrating Cultural Heritage into Smart City Development Through Place Making: A Systematic Review. *Urban Sci.* **2025**, *9*, 215. <https://doi.org/10.3390/urbansci9060215>.
38. TracePro. Available online: <https://lambdares.com/tracepro> (accessed on 1 December 2025).
39. Sydenham, P.; Thorn, R. *Handbook of Measuring System Design*; John Wiley & Sons, Chichester, UK, 2005; Volume 3.
40. Compagnon, R. Solar and daylight availability in the urban fabric. *Energy Build.* **2004**, *36*, 321–328. <https://doi.org/10.1016/j.enbuild.2004.01.009>.
41. Steadman, R.G. A Universal Scale of Apparent Temperature. *J. Appl. Meteorol. Climatol.* **1984**, *23*, 1674–1687. [https://doi.org/10.1175/1520-0450\(1984\)023<1674:AUSOAT>2.0.CO;2](https://doi.org/10.1175/1520-0450(1984)023<1674:AUSOAT>2.0.CO;2).
42. Watanabe, S.; Nagano, K.; Ishii, J.; Horikoshi, T. Evaluation of outdoor thermal comfort in sunlight, building shade, and pergola shade during summer in a humid subtropical region. *Build. Environ.* **2014**, *82*, 556–565. <https://doi.org/10.1016/j.buildenv.2014.10.002>.
43. Barroca, N.; Borges, L.M.; Velez, F.J.; Monteiro, F.; Górski, M.; Castro-Gomes, J. Wireless sensor networks for temperature and humidity monitoring within concrete structures. *Constr. Build. Mater.* **2013**, *40*, 1156–1166.
44. Jiang, F.; Ma, J.; Jin, Y. Unleashing the Potential of Large Language Models in Urban Data Analytics: A Review of Emerging Innovations and Future Research. *Smart Cities* **2025**, *8*, 201. <https://doi.org/10.3390/smartcities8060201>.
45. Zhang, L.; Chen, Z. Large language model-based interpretable machine learning control in building energy systems. *Energy Build.* **2024**, *313*, 114278. <https://doi.org/10.1016/j.enbuild.2024.114278>.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.